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Constraining General Two Higgs Doublet Models by the Evolution of Yukawa Couplings

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We analysis the constraints of the general two Higgs doublet models via evolving the Yukawa coupling constants to high energy under renormalization group. We consider the appearance of a Landau pole or large off-diagonal Yukawa couplings which cause tree level flavour changing neutral currents. Our study shows the latter condition can be used to answer that how much Z_2 symmetry breaking can be allowed in a given 2HDM model.

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1. Introduction

The two Higgs doublets model (2HDM) is the minimal extension of Standard Model (SM). The introduction of extra Higgs doublet can lead to the tree level flavour-changing-neutral-currents (FCNC), which should be strongly suppressed. Therefor it's necessary to restrict the general two Higgs doublets model in the Yukawa couplings sector. One of common ways is to impose Z_2 symmetry for the two Higgs doublets on the Lagrangian [1]. Under this symmetry there is only one Higgs doublet is allowed to interact with each type of fermions so that Yukawa coupling matrix is diagonal at any energy scale.

Recently a more flexible way of avoiding tree level FCNC has been proposed [2]. This idea simply requires that the two Yukawa couplings to the Higgs doublets should proportional to each other, so they can be diagonalized simultaneously. This restriction is fine in giving energy scale but the tree level FCNC will be reintroduced in higher energy scale [3]. There are also more general proposals which the tree level FCNC Yukawa couplings are suppressed enough, e.g. the Cheng-Sher ansatz [4].

We will study the properties of all these models by taking into account the theoretical and experimental constraints on FCNC. And then we will evolving all the Yukawa couplings to higher energy according to the Renormalization Group Equations (RGE). In some cases the off-diagonal matrix elements which relate to the FCNC grow quickly that indicates the certain assumptions behind the theory are not stale. Those theories are either fine-tuned or incomplete in certain way, e.g. there may be additional particles appearing when going to high energy scale.

2. The general 2HDM and RGE equations

One of standard convention to write the two Higgs doublets with the Goldstone bosons is

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \cos\beta - H^+ \sin\beta\right) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G^0\cos\beta - A\sin\beta\right) \end{pmatrix}, \tag{2.1}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \sin\beta + H^+ \cos\beta\right) \\ v\sin\beta + h\cos\alpha + H\sin\alpha + \mathrm{i}\left(G^0\sin\beta + A\cos\beta\right) \end{pmatrix}. \tag{2.2}$$

Where $G^\pm$ and G^0 are the Goldstone bosons to be eaten by the EW gauge bosons during EW symmetry breaking, and $H^\pm$ is the charged Higgs boson. The neutral Higgs scalar can be divided into CP even scalars (h,H) and CP odd pseudo-scalar A. α and β is the mixing angle between $(h,\ H)$ and the two vacuum expectation values (VEV).

For Yukawa coupling analysis, it's convenient to use Higgs basis

$$\begin{aligned} H_1 &= \cos\beta\,\Phi_1 + \sin\beta\, e^{-i\theta}\Phi_2\,, \\ H_2 &= -\sin\beta\,\Phi_1 + \cos\beta\, e^{-i\theta}\Phi_2\,. \end{aligned} \tag{2.3}$$

Where the nonvanishing VEV is only assigned to H_1 which plays the role of Standard Model Higgs doublet while H_2 contains the new partciels $H^\pm$ and A. The general Yukawa coupling is

$$\begin{aligned} -\mathscr{L}_Y = {} & \overline{Q}_L\widetilde{H}_1\kappa_0^U U_R + \overline{Q}_L H_1\kappa_0^D D_R + \overline{L}_L H_1\kappa_0^L E_R \\ & + \overline{Q}_L\widetilde{H}_2\rho_0^U U_R + \overline{Q}_L H_2\rho_0^D D_R + \overline{L}_L H_2\rho_0^L E_R + \text{h.c.}\,. \end{aligned} \tag{2.4}$$

Where the subscribe "0" stands for flavor basis. In mass basis, the 3×3 matrix κ^F is related to diagonal fermion mass matrix by using bi-diagonalizing with the unitary matrices V_L^F, V_R^F

$$\kappa^F = V_L^F \kappa_0^F V_R^{F\dagger} = \frac{\sqrt{2}}{v}\mathscr{M}_{ii}^F \tag{2.5}$$

The coupling matrix ρ^F is still general and complex if there are no further restrictions. The Cheng-Sher ansatz suggests

$$\rho_{ij}^F = \lambda_{ij}^F \frac{\sqrt{2m_i m_j}}{v}. \tag{2.6}$$

Where the m_i are the different fermion masses, the λ^F are expected to be of $\mathscr{O}(1)$ and should be small enough to suppress FCNC to the observed level. In EW scale, the Z_2 symmetric and aligned models can be teated as special case of Cheng-Sher ansatz.

3. Numerical analysis

3.1 SM input and Constraints

The most stringent constrains for tree level FCNC is from neutral meson mixing. The master formula for tree level $F^0-\bar{F}^0$ mixing can be found in [5].

Using current experimental and theoretical data, we estimated the bounds for nondiagonal λ_{ij}^F with the following assumption of Higgs scalar mass:

- $m_h = m_H = m_A = 120$ GeV: $\{\lambda_{uc} \lesssim 0.13, \lambda_{ds} \lesssim 0.08, \lambda_{db} \lesssim 0.03, \lambda_{sb} \lesssim 0.05\}$;
- $m_h = m_H = 120$ GeV, $m_A = 400$ GeV: $\{\lambda_{uc} \lesssim 0.30, \lambda_{ds} \lesssim 0.20, \lambda_{db} \lesssim 0.08, \lambda_{sb} \lesssim 0.12\}$.

According to these results, we choose $\lambda_{ij}^F \lesssim 0.1$ as a representive value which will be used as generic value later in RGE analysis.

3.2 Z_2 Symmetric Models

The first example we study is the models with Z_2 symmetry, in which the $\tan\beta$ is a physical parameter. The tree level FCNC is protected by the Z_2 symmetry, so the nondiagonal Yukawa couplings stay as zero in any energy scale. The only thing we can study is to detect the place of Landau pole, where at least one of the Yukawas blow up. Beyond the Landau pole the perturbation theory is not valid anymore.

In talbe 1 we show the diagonal λ_{ii}^F in terms of $\tan\beta$ for the four different 2HDM types in Z_2 symmetric models. The position of the Landau pole depends on the initial value of $\tan\beta$ in EW scale. In Fig. 1 we plot the upper and lower limit of $\tan\beta$. The plots can be understood by whether the evolution is driven by λ_{tt}, λ_{bb} ,$\lambda_{\tau\tau}$ or combination of them.

Type	λ^U_{ii}	λ^D_{ii}	λ^L_{ii}
I	$1/\tan\beta$	$1/\tan\beta$	$1/\tan\beta$
II	$1/\tan\beta$	$-\tan\beta$	$-\tan\beta$
III/Y	$1/\tan\beta$	$-\tan\beta$	$1/\tan\beta$
IV/X	$1/\tan\beta$	$1/\tan\beta$	$-\tan\beta$

Table 1: The diagonal λ^F_{ii} in 2HDM models with Z_2 symmetry.

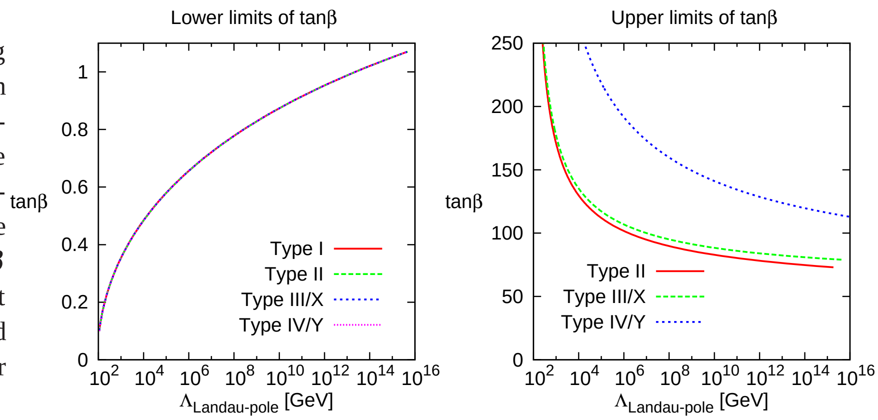


Figure 1: The starting value of $\tan\beta$ as a function of the position of the corresponding Landau pole ($\Lambda_{\mathrm{Landau-pole}}$) in the different 2HDM types. There are lower limits on $\tan\beta$ for all four types (left), but only type II, type III/X and type IV/Y have an upper limit of $\tan\beta$ (right).

3.3 Z2-breaking Models

3.3.1 Aligned models

In Yukawa alignment model, the two Yukawa couplings κ^F and ρ^F are proportional to each other so they can be diagonalized simultaneously. In this model the λ^F is also diagonal in EW scale. However the nondiagonl element will start to grow when the Yukawas evolve to higher energy via RGE. Similarly to the Z2-breaking models, we limit the alignment model with three different cases:

- Aligned I/II: $\lambda^U_{ii}, \quad \lambda^D_{ii} = \lambda^L_{ii}$
- Aligned III: $\lambda^D_{ii}, \quad \lambda^U_{ii} = \lambda^L_{ii}$
- Aligned IV: $\lambda^L_{ii}, \quad \lambda^U_{ii} = \lambda^D_{ii}$

In Fig. 2 we plot the energy scale at which the Landau pole or large nondiagonal $\lambda^F_{i\neq j} = 0.1$ is encountered as a function of pairwise combinations of the starting values for λ^U_{ii} and λ^D_{ii}.

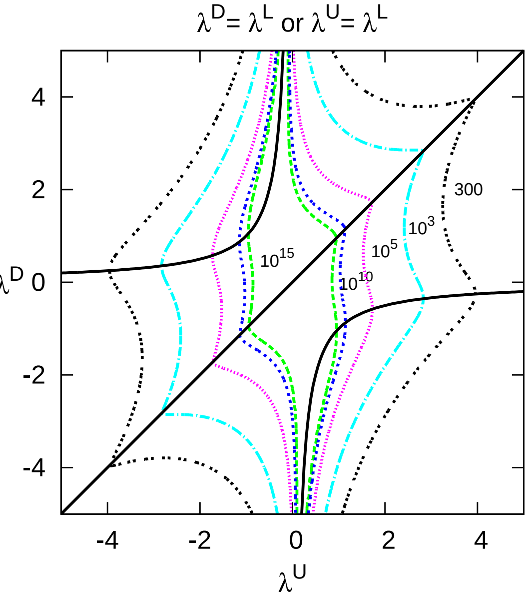
3.3.2 Diagonal models

Next we consider the models with Z_2 symmetry breaking in either the up or the down sector. First we break the Z_2 symmetry in the up-sector with $\lambda^D = \lambda_{tt}$ (type I) or $\lambda^D = -1/\lambda_{tt}$ (type II), and set $\lambda_{uu} = \lambda_{cc}$. Then we break the Z_2 symmetry in the down-sector with $\lambda_{bb} = \lambda^U_{ii}$ (type I) or $\lambda_{bb} = -1/\lambda^U_{ii}$ (type II), and set $\lambda_{dd} = \lambda_{ss}$.

3.3.3 Non-diagonal models

In the end we consider the models of Z_2 symmetry breaking from having non-zero non-diagonal elements in the up or down sectors. We set $\lambda^U_{i\neq j} = 0.1$ or $\lambda^D_{i\neq j} = 0.1$ at the EW scale

Figure 2: The constraints from the Landau pole and non-diagonal $\lambda^F_{i\neq j}$. The plot shows the same results for Aligned I/II or Aligned III. The λ^L_{ii} only play a very minor role so we don't show the plots for Aligned IV case. The areas inside a given contour are allowed by the requirement of the two condition above. The different contours are as follows starting from the center: 10^{15}, 10^{10}, 10^5, 10^3, and 300 GeV. The Z_2 symmetric case is also plotted as a reference.



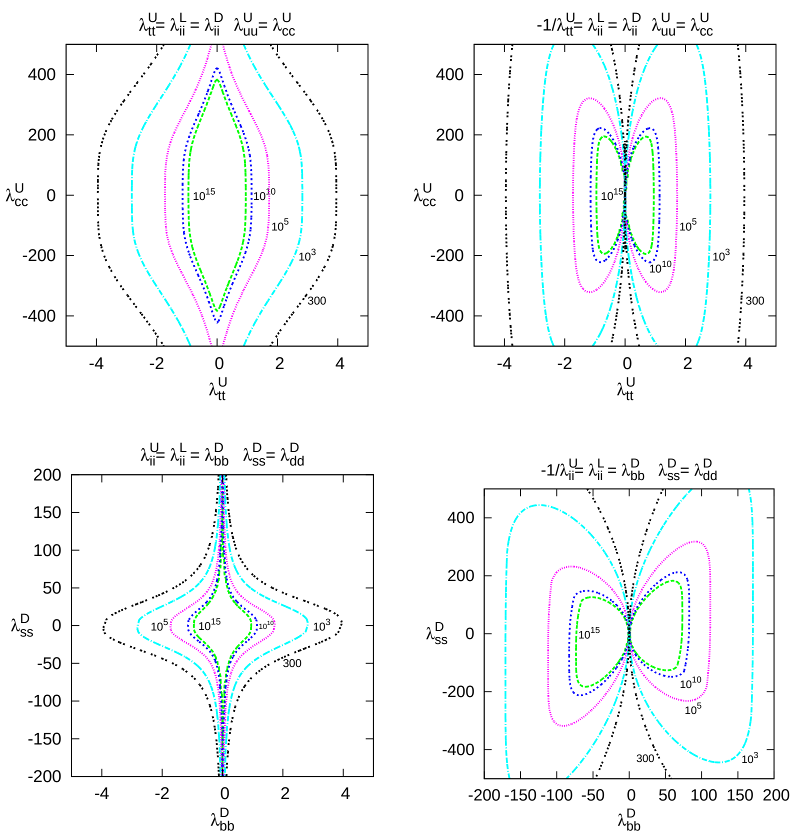


Figure 3: The energy scale where the Landau pole or non-diagonal $\lambda^F_{i\neq j} = 0.1$ is reached as a function of λ_{ss} and λ_{bb}. In the left (right) panels $\lambda^U = \lambda_{bb}(-1/\lambda_{bb})$ and in all cases $\lambda^L = \lambda_{bb}$.

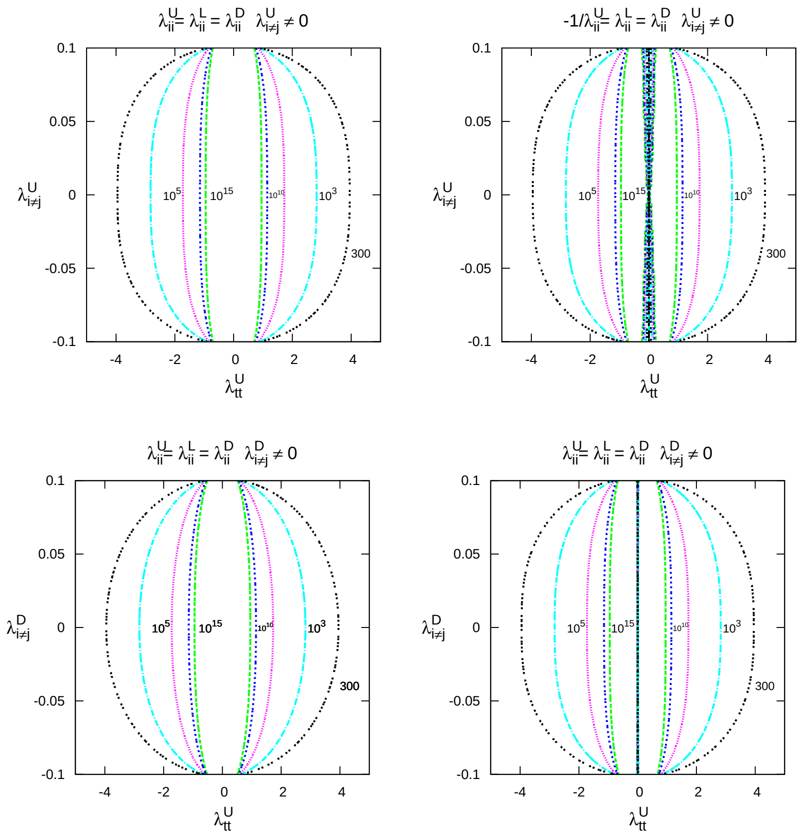


Figure 4: The constraints from the Landau pole and the off-diagonal elements as a function of λ_{ii}^{U} and the off-diagonal elements $\lambda_{i\neq j}^{U}$ (up) or $\lambda_{i\neq j}^{D}$ (down) at the input scale for the type I (left) and type II (right) relations for the diagonal elements.

and then evolve to higher energy. The analysis shows the constraints from off-diagonal elements are small compare to the previous cases.

4. Conclusions

RGE evolution is a useful tool to analysis different 2HDM models on stability of underlying assumptions. A quickly appearance of Landau pole or large off-diagonal Yukawa coupling under RGE evolution may indicate the model is either fine tuned or incomplete, e.g., new particles appearing in high energy.

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